REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(LEAVE BLANK)*

2. REPORT DATE
2/6/96

3. REPORT TYPE AND DATES COVERED
Final Report

4. TITLE AND SUBTITLE
Comprehensive Array Design System for Printed Circuit Antennas

5. FUNDING NUMBERS
DAAH04-95-C-0033

6. AUTHOR(S)
Dr. Peter T. Parrish
Dr. Gaofeng Wang
Dr. Scott W. Wedge

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Tanner Research, Inc. 180 N. Vinedo Ave., Pasadena, CA 91107

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Army Research Office
P.O. Box 122211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 34559.1-EL-SBI

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; SBIR report, distribution unlimited

19960521 037

13. ABSTRACT *(MAXIMUM 200 WORDS)*
Printed-Circuit antennas offer the potential for high gain, efficient, compact, light-weight, conformal antenna array systems. We have prototyped a Design Automation system consisting of design, simulation and synthesis tools targeted at Printed-Circuit array antenna development.

We have demonstrated this system by integrating our existing, graphical layout editor L-Edit™ and electromagnetic (EM) simulation tools, and have developed three application-specific Green's functions. We have supported industry standard geometry files for capturing existing designs, and we have demonstrated graphics and tabular display modules to display input impedance, S-Y-Z parameters, radiation patterns, gain and efficiency.

To demonstrate design entry, we have developed a small set of library elements for commonly-used feed elements, including parameterized elements to support tuning, sensitivity analysis, synthesis and self-adaptation algorithms.

The user-interface is layered, with options and technology-specific parameters and simulation options set to reasonable, default values for use by the novice designer, but configurable for customization by the expert designer.

We have studied and specified the requirements for antenna/array synthesis and enhanced EM simulation capabilities, including full-wave, multi-layer substrate, application-specific Green's functions. We have identified a full-wave approach, currently under development at Hughes Research Laboratories (Malibu, CA) that is particularly well-suited to PC antenna array validation.

14. SUBJECT TERMS
Antenna, printed circuit, computer aided design, array

15. NUMBER OF PAGES 33

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF THIS PAGE	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

Final Technical Report with DD250

January 19, 1996

Covering the Period June 1, 1995 to November 30, 1995

BAA number: BAA A94-030

Proposal Title:

Comprehensive Array Design System for Printed Circuit Antennas

Contract Number: DAAH04-95-C-0033

CLIN: 0002AB

Technical Point of Contact:

Dr. Peter T. Parrish
Tanner Research, Inc.
180 North Vinedo Avenue
Pasadena, CA 91107
Phone: (818) 432-5731
Fax: (818) 792-0300
e-mail: peter.parrish@tanner.com

Contractors type of business: OTHER SMALL BUSINESS

Distribution List

Recipient:	**Quantity:**
US Army Research Office Attn: AMXRO-ICA (Ramseur) P.O. Box 12211 Research Triangle Park, NC 27709-2211	**3**

Table of Contents

Introduction

Printed Circuit antennas possess a number of attractive properties that make them ideal candidates for use in compact, portable communications and radar systems. They are:

- Compact
- Light-weight
- Low-cost
- Easy to fabricate
- Conformal
- Easy to integrate with feed and matching network

Perhaps the simplest configuration of a PC antenna is a metallic patch—of square, rectangular, circular, triangular, or more complex shape—patterned on a dielectric substrate of one or more layers. The shape of the radiating element depends on the parameters to be optimized: bandwidth, side lobes, cross-polarization. Since elements radiate close to their resonant frequencies, their dimensions are on the order of a half wavelength. When combined into arrays, PC antennas offer all of the above advantages, but with radiation pattern flexibility, as well.

Our Phase I study contract called for us to first define and then to prototype the components of a comprehensive array design system for printed circuit antennas. To date, most PC antenna design is performed in a rather *ad hoc* manner, using a motley collection of software programs to solve specific problems related to layout and analysis. Our efforts have been oriented toward developing an *integrated* software design solution that tackles all aspects of antenna design. To this end, we have identified the following functions that must be handled in the integrated tool:

- Layout of the antenna elements and the corporate feed system
- EM and circuit-level analysis of the antenna array system
- Array synthesis and design verification

To prototype the functionality we believe is necessary for our overall software design system, we have weaved together several Tanner Research software products—and developed a few more from scratch—in order to evaluate the technical feasibility of a comprehensive PC antenna array design and analysis tool suite.

Our prototype is based on modifications to the following Tanner Research tools:

- Layout editor—L-Edit™
- Graphics/visualization tool—W-Edit™
- EM analysis engines—L-Edit/2DEM™ and L-Edit/3DEM™
- EM analysis manager—TLExtract™
- Frequency domain circuit simulator—Puff™

In addition we have developed "from scratch" two EM analysis engines for the analysis of far-field antenna patterns and driving point impedance:

- Transmission line Model for rectangular patches
- Cavity Model for rectangular and circular patches

The concept of library elements was developed, both for simple patch antenna elements and for feed structure components. Each library element consists of a layout cell and a companion simulation model. Wherever practical, a library element was parametrized, so that a single element could cover a range of dimensions, material properties and configurations.

The concept of an *analysis manager* was introduced to prepare a design for analysis by creating a simulatable netlist in the most expeditious manner. The analysis manager identifies elements of the design for which models already exist, identifies structures which need EM analysis, and decides, in this latter case, which EM engine is the most appropriate. Far-field antenna patterns are obtained as well as system quantities such as impedance and efficiency. Finally, the analysis manager assembles the model and their connectivity in a netlist suitable for simulation using a circuit simulator (either time-domain or frequency domain) to obtain the effects of the corporate feed structure.

This overall approach is aimed at capturing an antenna design and performing a reasonably accurate analysis in a matter of hours using desktop-class workstations. Continual refinement of the design can now take place by "tuning" the elements parameters until the design has been optimized.

An "optimum design" based on this approach, has certain limitations based on the assumptions underlying the steps in the approach itself. The use of models and circuit-level simulation techniques, assumes that well-defined, and well-characterized interfaces exist between the discrete elements. Moreover, it assumes that elements can be modeled in isolation without concern for coupling between the elements. To test to what extent these assumptions are true, more exact EM analysis can be performed. We refer to this step as design validation.

Design validation of the corporate feed design would involve the analysis of whole sections of the feed using a full-wave EM simulator and comparing the model results. Design verification of the antenna array would involve the analysis of the whole array at once, again using full-wave techniques. Array verification would be a time-consuming endeavor and every effort should be made to develop a full-wave EM engine that optimizes both accuracy and simulation speed.

1 A Layout Editor for PC Antenna Arrays

This task consisted of two steps: (i) analyzing the features needed to support physical design entry for PC antennas and feed structures and (ii) the evaluation of Tanner's layout editor L-Edit as a candidate tool for that purpose.

1.1 Regions

We have determined that the L-Edit GUI will allow the user to input all required geometrical, electrical and technology-specific information required for PC antenna analysis. PC antenna structures can be defined using three types of three-dimensional (3-D) *regions*:

- Conductor Regions: Conductors include radiating structures, feed lines, vias and other vertical feed structures, pads, and ground/power planes.
- Dielectric Regions. Dielectrics are most often encountered as substrates, but are also used for conformal coatings, spacers and other mechanical functions.
- Aperture Regions. An aperture is hole in a conducting plane (e.g. ground or power). It can be used (i) to couple energy electromagnetically (e.g. from a feed line below the ground plane, to a radiating patch above the ground plane) or (ii) to permit the passage of a "via" or other vertical feed structure through a plane without shorting to it.

Using L-Edit, the user can create antenna structures by drawing *objects* representing the 3-D structures including conductors, dielectric regions, and holes. In the standard view, these objects are rendered as top views of the X-Y plane. L-Edit also contains a cross sectional viewer, which is discussed in Section 1.3.

There are three steps in the L-Edit object editing procedure:

- Selecting the desired *technology layer*
- Selecting the desired *drawing tool* from the tool palette
- Drawing the *object* on the screen.

The *technology layer* is used to associate the following electromagnetic and specialized dimensional data:

- Electric properties, including relative dielectric constant and loss tangent for dielectrics, and resistivity for metals,
- Geometrical data, including baseline position and thickness (in the Z-dimension).
- Mesh specification: either the mesh grid length (e.g. 100 μm) or mesh density (e.g. 100/mm^2).

All objects drawn on the same *layer* inherit the properties associated with that layer. For example, all the objects drawn on the same layer will have the same baseline position and thickness.

The geometrical data of layout of 3-D EM objects are captured by creating their layouts on the screen with the selected *drawing tool.* The L-Edit layout editor supports five drawing tools:

- Rectangle
- Circle
- Polygon
- Wire
- Port

The first four drawing tools are used to create the X-Y geometries. The port tool is used to tag an L-Edit object for the purposes of identifying ground planes, feed lines, radiating elements, feed position and waveforms (time domain excitation of the network).

1.2 Copies, Instances and Arrays:

A group of *objects* can be *copied*, creating a duplicate of the original objects. The *repeated copy* operation will also be available, but for more than a few copies, the *array* function will be used (see below). The copy, although an exact duplicate, has no linkage to the original object (e.g. if the original object is modified, the copy will not be modified).

A *cell* is composed of two major components: the *primitives* (e.g. objects) and *cell instances* (i.e. linked copies of other cells). Cell instances inherit all of the dimensions and layer properties of the original cell (e.g. if the original cell is modified, the instance reflects that modification), and can be scaled and translated and made into arrays. Cells will be created to produce a distinct functional module within a design. A *library* of standard cells (i.e. cells that will be used as functional building blocks in a more complex design) will be created to decrease the design cycle time and improve design quality. For example, a rectangular patch element could be a standard cell that could then be instanced into an array to form the PC antenna.

Cell instances are created by specifying the following information:

- Cell name
- Instance name
- X and Y scale factor (magnification)
- X and Y translation
- Array Parameters: X and Y repeat count, X and Y offsets

Using cells is a powerful way to build library elements. A standard set of library elements can be created, using the proper layers and design rules for a given manufacturing process. Using the scale factors and translation, modifications to the standard elements can be made to incorporate new elements as required. Finally, the array can be used to build antenna arrays automatically from single elements.

Changing cell or array dimensions is very straightforward, allowing tuning or "what if" calculations to be performed quite easily.

An example showing the utility of using cells and instances to produce antenna array is shown in Figure 1-1, below.

1.3 Cross Sectional Viewer

Since PC antenna technology is inherently three-dimensional, quick access to cross-section views is an effective way to communicate the relevant content of an antenna design that may not be readily apparent from the X-Y or "top" view. In order to implement this feature, L-Edit has a "Cross-section Process" file. This file consists of a series of fabrication steps—grow/deposit, etch and implant/diffuse—applied sequentially from the substrate up, one layer at a time.

The display of the cross-section is viewed in the lower half of a "split screen", with the normal, X-Y view in the upper half. A sectioning line is created using the mouse in the X-Y view, and can be moved as desired to view different X-Z cuts.

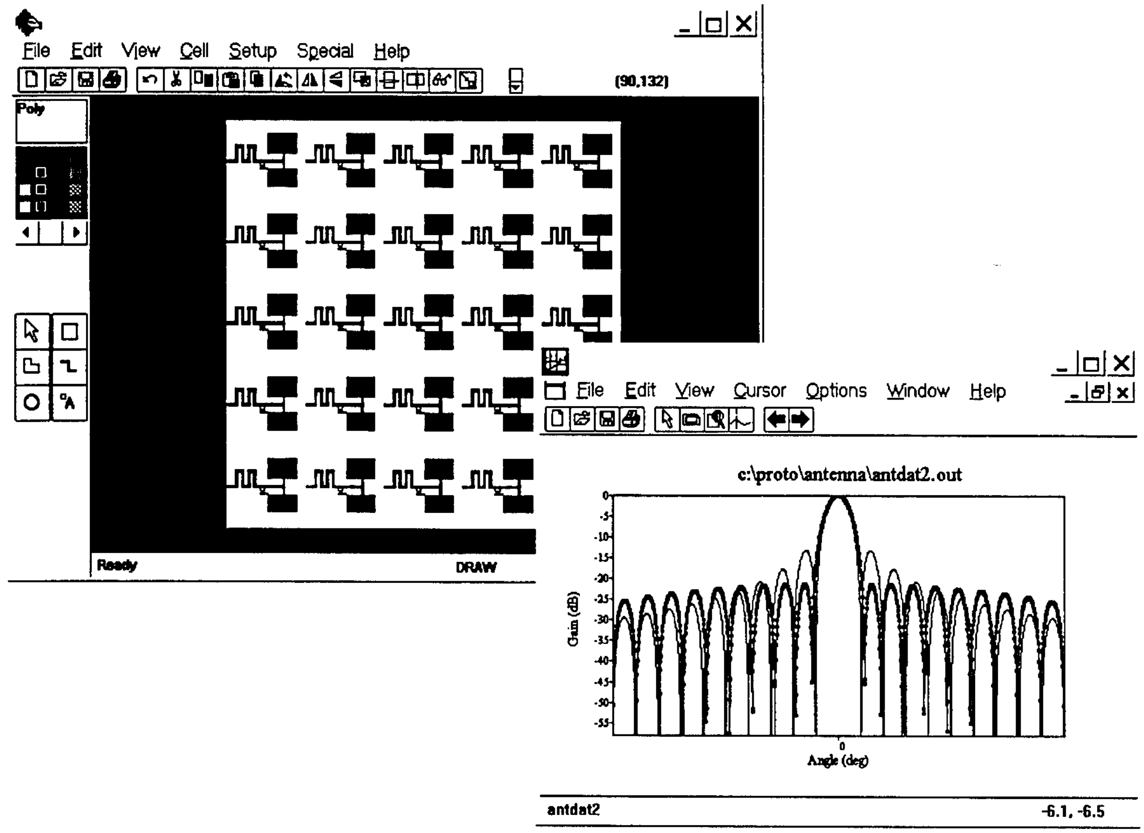

Figure 1-1: The L-Edit window depicts a 5x5 array of patch antenna with microstrip meander line matching section. W-Edit window depicts an antenna pattern with a Taylor distribution. Both L-Edit and W-Edit are running under Windows 95.

1.4 Design Rule Checking (DRC)

In order to insure that a PC antenna design falls within the constraints of an actual fabrication process, a DRC is available within the L-Edit design environment. The DRC function is based on a set of geometrical constraints which are applied to the design. The constraints include a set of minimum allowable values for *certain widths, separations, extensions*, and *overlaps* of geometrical objects patterned in the various levels of a design. A *design rule database* is included in the design database and is used to perform the DRC on a design.

The DRC violations are reported three ways (selectable by the user):

- Placing *error ports* on the layout at violation locations
- Placing *error markers* at violation locations, and/or
- Writing the results to a *text file.*

1.5 Geometrical Design Import/Export Capability

Antenna systems that are fabricated using multi-layer printed circuit board processing techniques are particularly well suited to design representations that are based on a X-Y-

Layer paradigm. In order to *visualize* this type of data representation, a mapping from layer to Z-baseline and object thickness is required. More sophisticated mappings can include Z-axis taper (e.g. processing steps that produce sloping side walls). A Cross Section Viewer is a standard feature in Tanner's L-Edit tool. With the specification of a Process Definition File, cross sectional views can be generated from a cut perpendicular to the X-Y plane.

In terms of exporting the design data, two popular industry standards for IC-processing data, and Tanner Research's approach to 3-D visualization will be described in the following sections.

1.5.1 Calma Graphics Design System (GDSII):

GDSII supports a set of two dimensional objects (i.e. *elements* in GDSII terminology). 2D objects include closed polygons (*boundaries*), open polygons (*paths* with *width* and *pathtype*). GDSII supports instances (*structure references*) and arrays (*array references*). The objects are organized by *layer* and can further be differentiated by *datatype*. Additional properties supported include placement, rotation, magnification and reflection.

1.5.2 Caltech Intermediate Format ("CIF"):

CIF is defined in *Introduction to VLSI Systems* (C. Mead and L. Conway, Addison and Wesley, 1980). CIF also supports a set of 2D objects, including closed polygons and paths (*wires*), rectangles (*boxes*) and circles (*roundflashes*). Layer is supported but datatype is not. Additional properties supported include placement, mirror-X and mirror-Y, rotation, but not magnification.

1.5.3 Extensions to GDSII and CIF:

It is highly desirable to link layout and nodal connectivity. Tanner supports a layout-nodal connectivity link by associating named ports with a layout element. Once created and associated with a layout element, ports can be used to establish connectivity between two objects by wiring two of their ports together as a *common node* (i.e. giving them the same port name). This functionality is used by Tanner Tools to compare schematics and layout and to guide circuit routing.

In order to support the export of nodal as well as geometric information, we have implemented the following extensions/conventions to GDSII and CIF file formats:

- Support for ports for CIF export has been implemented by creating a Tanner extension to the CIF specification, which has become a standard notation for CIF ports readable by many third-party software tools (c.f. L-Edit User Manual, Version 5.0, p. 22-7).
- Support for ports for GDSII export has been implemented by using GDSII text elements with the port location corresponding to the GDSII text origin and the port name corresponding to the GDSII text string (c.f. L-Edit User Manual, Version 5.0, p. 23-1 through 23-4).

1.6 Antenna Element Library

We envision this to be a major Phase II task. It will necessitate understanding not only the technology specific issues but application issues as well. For the purposes of our

Phase I study, we developed two radiating patch elements (rectangular and circular) and a set of interconnection or circuit elements (basic microstrip transmission line, the right angle bend, open circuited and "tee"). These circuit elements have been used to match a radiating patch to 50Ω at its resonant frequency.

We anticipate that a practical library should include a rich set of radiating patches and apertures as well as a complete set of transmission line elements that would be needed for feed structure development. We have preliminarily identified the following preliminary list of library elements:

Antenna Patch Library Elements	
• Rectangular	• Two-port
• Circular	• Inset excited
• Edge excited	• Aperture coupled
• Aperture excited	• Slot coupled
• One-port	

Interconnect Library Elements	
• Transmission line	• Coupler (e.g. branch line, rat race)
• Tee (three-way junction)	• Via (antenna to transmission line)
• Cross (four-way junction	• Via (transmission line to ground)
• Coupled lines (2 at least)	• Thin film capacitor
• Open- and short-circuited stub	• Thin film resistor
• Bend (all angle, chamfer option)	

1.7 Synthesis of the Corporate Feed Structure

The corporate feed structure consists of a power distribution and phasing network, and the individual antenna feed configuration. The exact feed geometry depends on the transmission line medium used. Edge-fed antennas can be realized on the same substrate surface using a microstrip or co-planar line. Aperture-fed and slot-fed antennas can be realized using reactive coupling through a ground plane hole with buried transmission media (e.g. stripline). Inset-fed antennas can be realized using vertical feed structures (e.g. coax) and backside microstrip, coplanar or stripline.

We have developed an approach which is independent of the feed geometry and transmission medium, that simplifies design and reduces simulation time using frequency-domain circuit simulation techniques. Through our layout library, a rich set of transmission line component and antenna feed models will be available for stripline and microstrip, and coplanar media.

1.7.1 Feed Structure Synthesis

To facilitate the potentially tedious task of placing transmission line components and routing transmission lines for the corporate feed structure, performance-based placement and routing algorithms will be developed. The output of the array synthesis will be a map of antenna element locations. Choosing a specific radiating patch or aperture will define the exact feed points. Another output of the synthesis program, will be the amplitude and phase taper to be applied to each element. As the designer places and routes each component and transmission line element, phase and amplitude information will be automatically be updated, providing guidance to the designer.

1.7.2 Feed Structure Models

In order to take advantage of circuit simulation techniques, there must be accurate, frequency-domain models for each of the transmission line media (e.g. stripline, microstrip or coplanar), common discontinuities (e.g. steps, bends and junctions) and other common power and phase conditioning elements (e.g. hybrid couplers).

If custom structures are encountered in a design, 2DEM and 3DEM engines will be available to provide frequency-domain models for these structures. If active devices are need used in the corporate feed network, *n*-port S-parameter models can be used.

2 Graphics/Visualization for display of analysis results

W-Edit™, Tanner Research's graphics visualization tool will be used as the prototype for displaying PC antenna analysis results. We have identified three major areas for display support:

- General capabilities
- Support for circuit-based results
- Support for combined layout and simulation display
- Support for antenna and array patterns

General capabilities include the standard operations of such as undo and nested undo. Units include automatic display and recognition of engineering units and elementary trace operations. Plot types include real and complex numbers, false color for scalar field distributions, vector field plots, logarithmic plots, parametric plots and polar plots.

The should also be support for line styles, symbols, labels, fonts and tiles. Cursor support should include intersection vs. X-value line, X-Y position and slope vs. cursor crosshair, parameter value vs. Crosshair and peak value (interval and global).

In addition to these general capabilities, there are special needs for circuit simulation, EM/thermal analysis and antenna patterns:

Circuit Simulation:

- Impedance and admittance vs. frequency
- Smith chart display

Combined layout and simulation display

- Current density on transmission line
- Scalar/vector E-field and H-field in dielectric regions

Antenna and array patterns

- Gain/polarization/cross-polarization/directivity vs. angle

Parametrized vs. frequency, phase shifter state,

- Rectangular and polar plots
- Magnitude/dB plots

Antenna Pattern Post Processing

- Gain, directivity
- Antenna efficiency
- Beamwidth, Beam solid angle

Figure 2-1 shows a W-Edit V2.0 display window with two antenna patterns, with automatically scaled display.

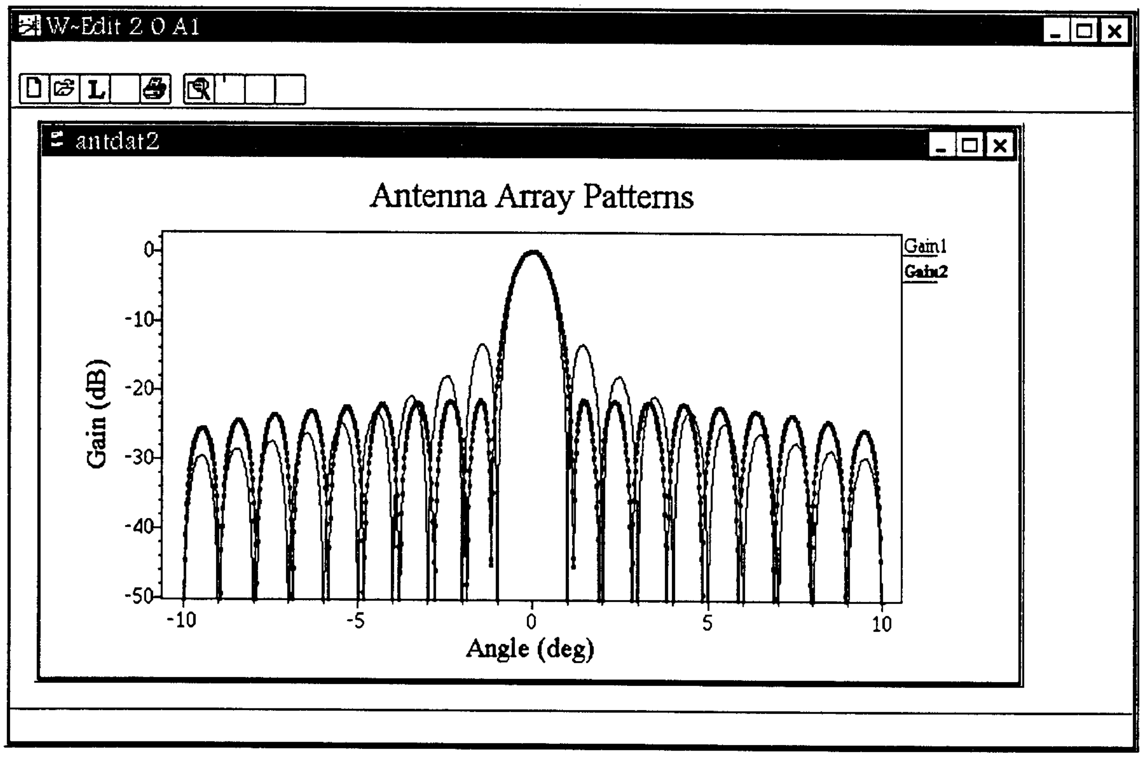

Figure 2-1: Far-field patterns for a uniformly distributed array and a Taylor array displayed using W-Edit.

3 Antenna Element Analysis

3.1 Analysis Manager

We have developed a prototype Analysis Manager to assist in the efficient extraction and analysis of antenna systems. Brute force EM simulation of an entire antenna system is a major undertaking but more importantly *unnecessary*. Most if not all of the interconnect subsystem should be analyzed by a circuit simulator using models from the Interconnect Library. Custom structures, when used, will need an EM analysis, generating the model in an *in situ* manner. We anticipate that a similar situation will evolve over time for radiating elements as antenna design matures and becomes more of a "mainstream" design activity.

It is the role of the "extractor" to search the design space identifying structures for which models already exist and structures which require EM analysis. The extractor performs its initial identification based a set of rules, using layer, layer properties and geometrical information. For example, a single microstrip transmission line can be identified and extracted if an object resides on layer with an adjacent ground plane layer. If the object consists of a rectangle, then the extractor maps the rectangle length and width into the microstrip line length and width. The layer thickness attribute is mapped into the microstrip metal thickness.

The extractor will also be able to decide which structures can be analyzed individually, and those that need to be analyzed together due to anticipated coupling between them. For example, the extractor can be programmed by the user to identify coupled lines by searching the design for objects on the same layer separated by a maximum distance or less and are collinear for a minimum distance. The extractor can also be programmed to "ignore" objects of a certain size or less, mapping them into isolated electrical short circuits. Finally, the extractor builds a simulatable netlist, inserting model statements for the all elements in the design. As stated above, the model statements can be library models or be *in situ* models created by EM simulation.

3.2 EM Engines for PC Antenna Analysis

Many different approaches at various levels of approximation and sophistication have been developed to analyze the large variety of microstrip antennas encountered in applications. Simple models, such as the transmission line model or the cavity model, are applicable when substrates are electrically thin, typically less than $0.1\lambda_g$. These models provide a first-order approximation to the radiation pattern of the antenna but do not take into account surface waves [1]. A more refined analysis requires the use of full-wave analysis methods utilizing rigorous electromagnetic techniques [1].

Our goal is to develop an optimally-configured EM simulation environment that employs multiple EM engines, each of which has been optimized to a particular class of radiating structures encountered in the PC antennas.

There exists a trade-off between simulation accuracy and simulation complexity of EM engines. In order of increasing simulation accuracy and complexity, the EM engines for PC antenna analysis can be classified into four analysis categories:

- Transmission line model
- Cavity model
- Multiport-network approach
- Full-wave analysis.

In addition, the analysis of PC antenna arrays can be also classified to three possible levels:

- Synthesis
- Infinite periodic array analysis

- Finite array analysis

3.2.1 The Transmission Line Model

In this model a rectangular microstrip antenna patch is viewed as a resonant section of a microstrip transmission line. A detailed description of the transmission line model is given in [1]. The different variants of this model were developed in [2-5].

There are several limitations inherent in the concept of the transmission line model for microstrip antennas. The basic assumptions are (i) fields are uniform along the width of the patch and (ii) there are no currents transverse to the length of the patch. But analysis of rectangular elements shows that even at a frequency close to the resonance, field distribution along the radiating edge is not always uniform. Also, the transverse currents have been shown to be caused by the feeding mechanism.

Our transmission line model implementation—based on the work of Hammer et al [33] and Pues and van de Capelle [34]—is a model which gives reasonably accurate far-field antenna patterns and driving point impedances with very fast simulation times (0.5 seconds on a 90 Mhz Pentium PC). Figure 3-1 depicts a rectangular antenna of patch width W and length L, where L is the "resonant" dimension of the fundamental radiating mode. There are two basic assumptions: (i) fields are uniform along the width of the patch (no transverse mode excitation) and (ii) there are no currents transverse to the length of the patch. Our implementation of this model supports a "feed" at any point along the length of the patch. The limitations of the transmission line model are the following:

"Thin substrate": $h \prec \frac{1}{10\sqrt{\varepsilon_r}}\lambda_o$

Near resonance of the fundamental mode: $L = \frac{1}{2\sqrt{\varepsilon_r}}\lambda_o$

A specification of the algorithms used to develop the Transmission line model code is contained in Appendix A.

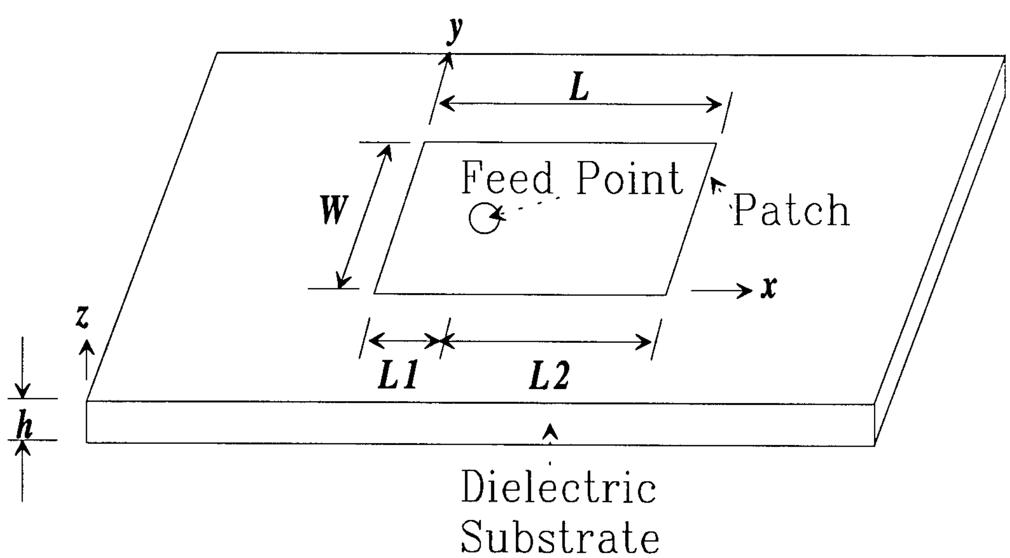

Figure 3-1: Layout of rectangular patch antenna for transmission line analysis

The analysis results for an example antenna, designed to resonate at 10 Ghz, are shown in Figures 3-2 and 3-3, using the parameters in Table 3-1.

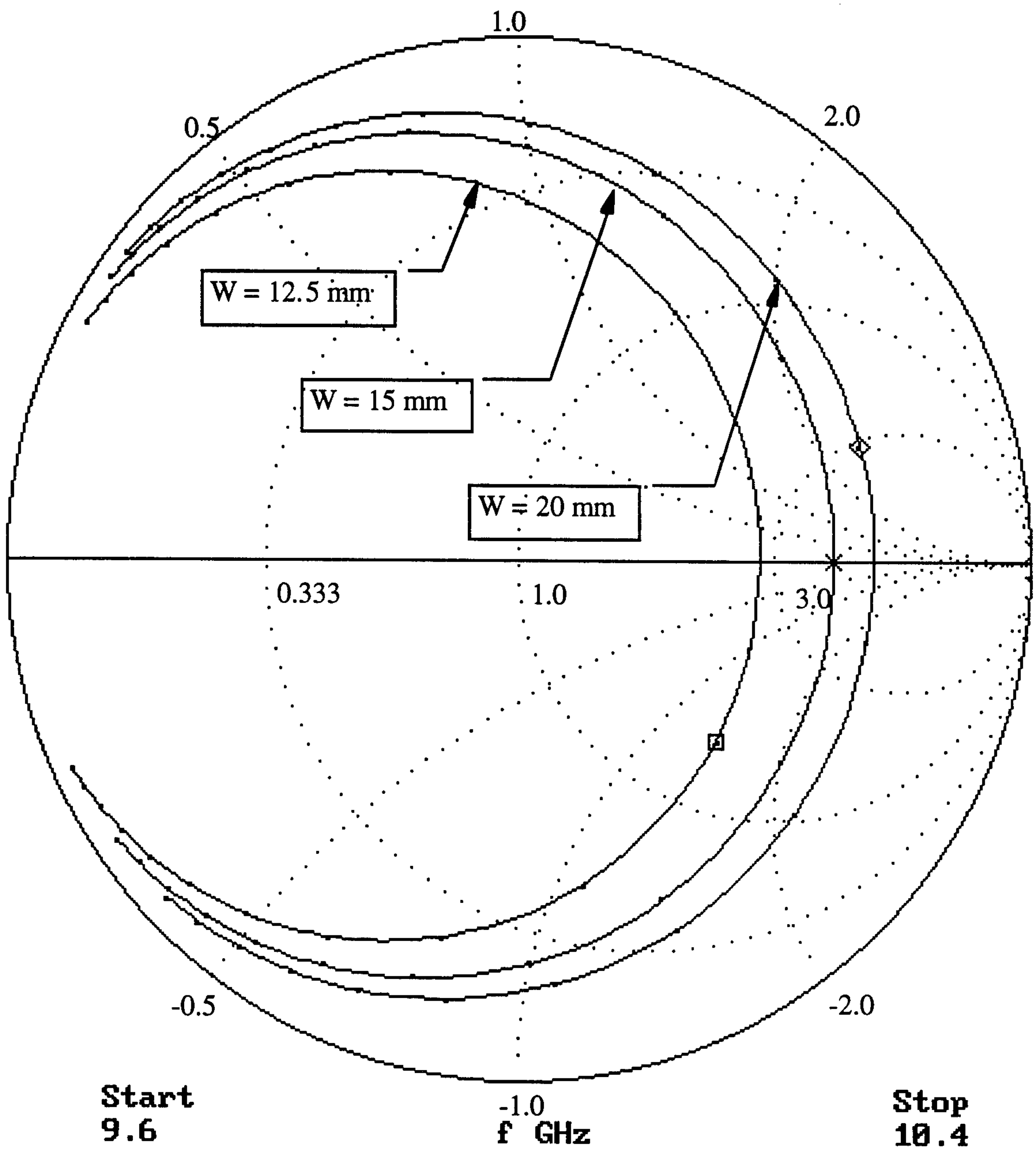

Figure 3-2: Smith Chart plot of input impedance for rectangular patch antenna using parameters in Table 1. Square, cross and diamond markers represent 10 Ghz.

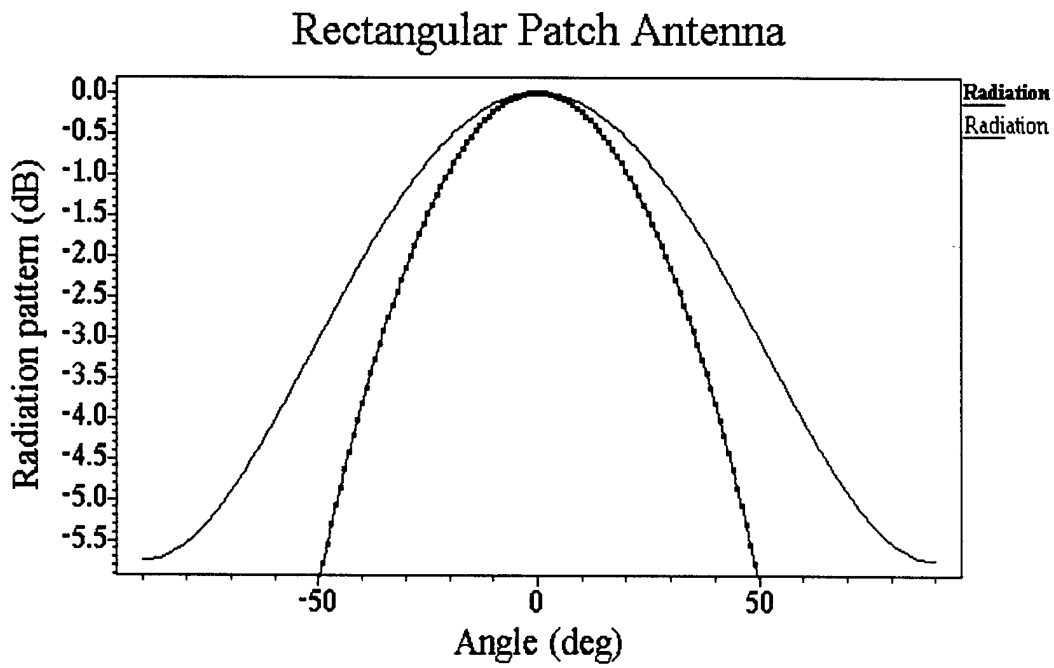

Figure 3-3: Antenna patterns for parameters given in Table 1 (E-plane -----, H-plane -•-•-•)

$h = 250\ um$	$t = 2\ um$
$\varepsilon_r = 2.30$	$tan\,\delta = 0.001$
$L = 9.8042\ mm$	$W = 12.5, 15, 20\ mm$

Table 3-1: Patch antenna dimensions and material properties

3.2.2 The Cavity Model

A planar two-dimensional cavity model for microstrip patch antennas [6-9] offers considerable improvement over the one-dimensional transmission line model. In this method the microstrip patch is considered as a two-dimensional resonator surrounded by a perfect magnetic wall. This model is best suited for geometries in which the Helmholtz equation possesses an analytical solution, such as disks, rectangles, triangles or ellipses. It assumes that the substrate thickness is much smaller than a wavelength. More complex shapes can then be analyzed by segmentation and desegmentation techniques [10, 11].

The cavity model approach can be employed to analyze various patches of regular shape. The cavity model is a two-dimensional model, which offers considerable improvement over the one-dimensional transmission line model. Moreover, the cavity model can be extended into multiport network model, to allow more general shapes through the segmentation and de-segmentation techniques.

We have implemented a prototypical cavity model to analyze rectangular and circular patch antennas. The primary scheme for the radiation pattern calculation was based on the article "Theory and Experiment on Microstrip Antennas" by Lo, Solomon and Richards [7]. The primary scheme for the input impedance calculation was based on the article "An Improved Theory for Microstrip Antennas and Applications" by Richards, Lo and

Harrison [9]. The cavity model gives accurate far-field antenna patterns and driving point impedances with fast simulation times (43 seconds on a 90 Mhz Pentium PC). It supports arbitrary feed point location.

A specification of the algorithms used to develop the Cavity Model code is contained in Appendix A.

A cavity model for the microstrip antennas is based on the following observations: (a) The close proximity between the microstrip antenna and the ground plane suggests that the electric field $\boldsymbol{E}$ has only the z-component and $\boldsymbol{H}$ has only xy-components in the region bounded by the microstrip and the ground plane. (b) The in fields this region are independent of the z-coordinate. (c) The electric current in the microstrip must have no component normal to the edge at any point on the edge, implying a negligible tangential component of $\boldsymbol{H}$ along the edge. Therefore, the region between the microstrip and the ground plane can be treated as a cavity bounded by a magnetic wall along the edge and by electric walls from above and below. Radiation patterns are computed by solving for the currents on the magnetic walls, and by then computing the far-field patterns from these currents. The geometry for the circular patch antenna is depicted in Figure 3-4.

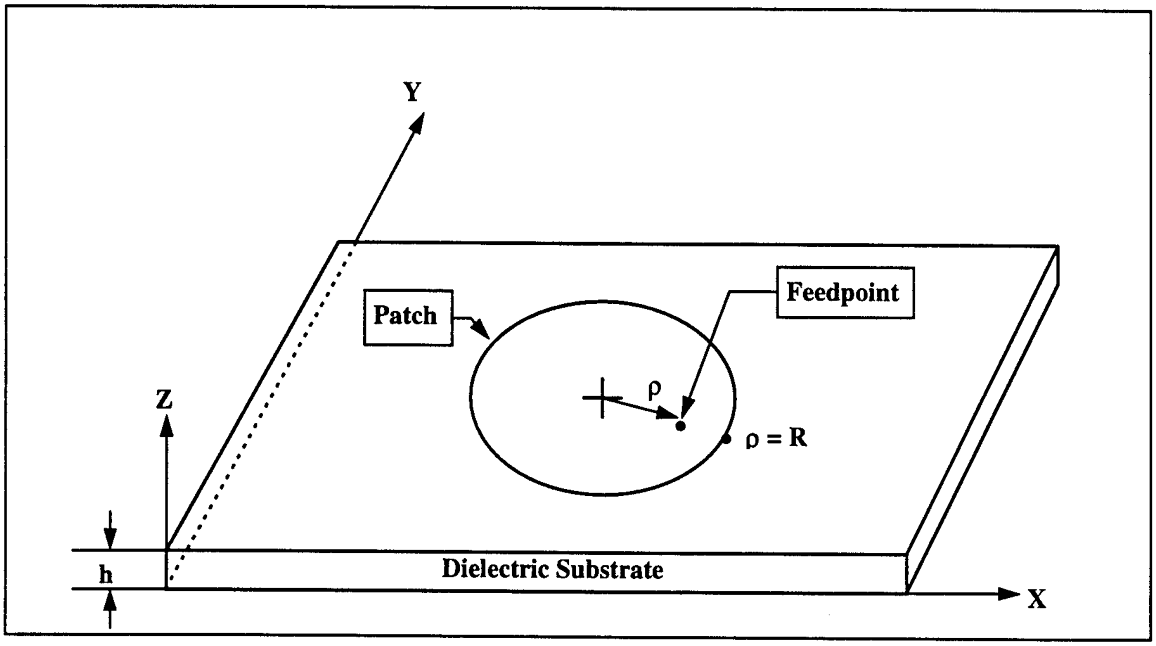

Figure 3-4: Geometry of the circular microstrip antenna.

A specific X-band design example of a Copper, PTFE circular patch antenna has been analyzed using the cavity model. The substrate dielectric constant and loss tangent are $\varepsilon_r = 2.30$ and $tan\,\delta = 0.001$, respectively. The patch metal thickness and electrical conductivity are $t = 2\mu m$ and $\rho = 5.813 \times 10^7\ S/m$, respectively. We adjusted the patch radius to $R = 5.79375\ mm$ to obtain a resonant frequency of 10 Ghz for $\rho = R$. This antenna is assumed to be fed by a 50 ohms microstrip line or coaxial line. These parameters are summarized in Table 3-2, below. Figure 3-5 depicts the input reflection coefficient loci over frequency, for different values of ρ. Figure 3-6 depicts the radiation pattern of this antenna for the case $\rho = R$ and for the resonance at 10 Ghz. As the feed point moves from the edge of the circular patch towards the center, the resonant frequency changes from 10.00 Ghz to 10.01 Ghz, a very small amount. The radiation resistance, however, moves from 169 Ω (for ρ=1.0·R), to 62.9 Ω (for ρ=0.41·R), to 17.9 Ω (for ρ=0.21·R).

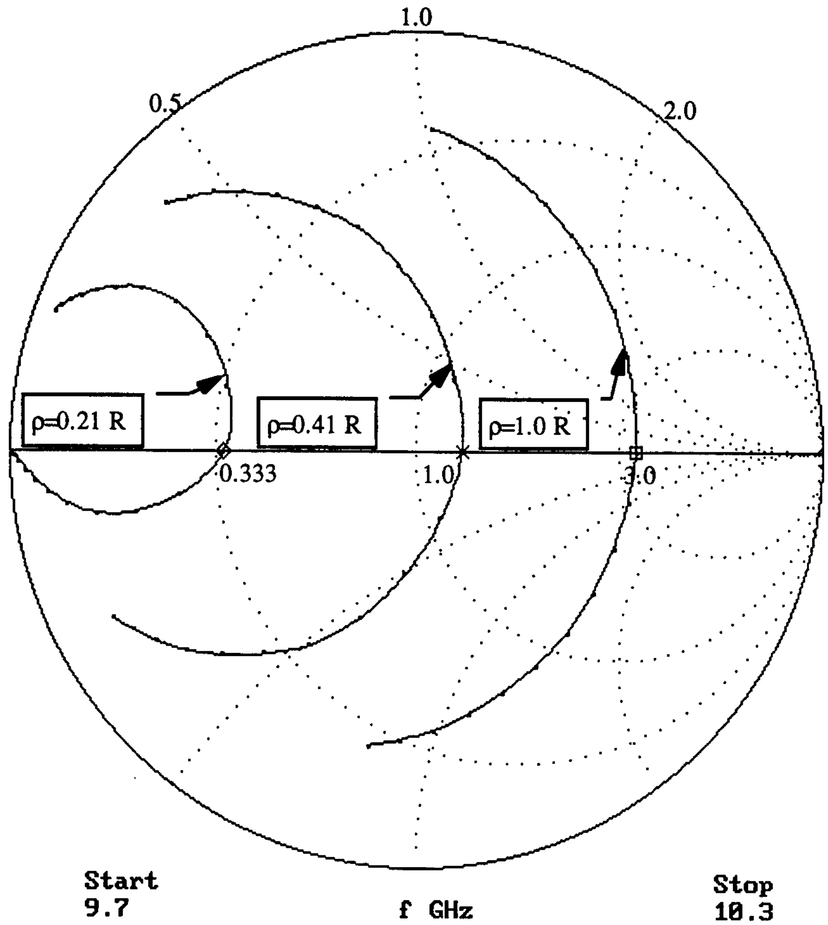

Figure 3-5: Smith Chart plot of the input reflection coefficient for the circular patch antenna, with R=5.79375mm and varying feed point radii. Reference impedance is $Z_o = 50\ \Omega$

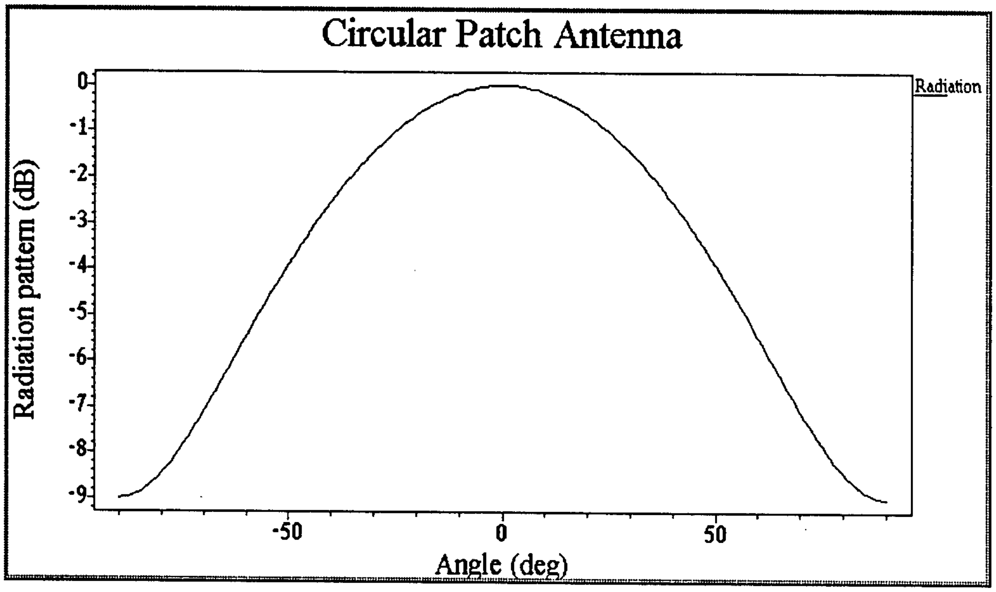

Figure 3-6: Far field antenna pattern at 10 Ghz and for ρ=R=5.79375mm.

$h = 254\ \mu m$	$\varepsilon_r = 2.30$
$t = 2\mu m$	$tan\,\delta = 0.001$
$R = 5.79375\,mm$	$\rho = 5.813 \times 10^7\ S/m$
$\rho/_R = 0.21, 0.42, 1.0$	

Table 3-2: Patch antenna dimensions and material properties

3.2.3 The Multiport-Network Model

In the multiport-network modeling approach for radiating microstrip antennas [12, 13], the fields underneath the patch, the external fields and the fields underneath the microstrip feedlines are modeled separately in terms of multiport subnetworks. The fields on either side of an interface between any two subnetworks are matched at discrete number of points by subdividing the common interface into a number of sections. Matching of the fields is achieved by satisfying equivalent Kirchhoff's network relations at those interconnecting ports. Equating the voltages at the connected ports is analogous to matching the tangential E field and the continuity of currents ensures the continuity of the tangential **H** field at the interfaces. The multiport subnetworks are characterized in terms of either **Z** matrices of **Y** matrices and are combined together using the segmentation technique [10] to obtain the antenna characteristics. In this approach the substrate material is assumed to be nonmagnetic. The ground plane and the dielectric substrate are assumed to be infinite in extent. The multiport-network modeling approach incorporates the effect of the edges [13, 14], and mutual coupling [15, 16].

3.2.4 Full Wave Analysis

All techniques discussed above are based on two-dimensional formulations and are very computationally efficient. The Full-wave analysis methods utilize more rigorous electromagnetic techniques at the expense of computation time. The most commonly used method for full-wave analysis of PC antennas makes use of an integral equation formulation for current distribution on the elements. Different variations of the integral equation approach have been developed. A method known as electric field integral equation (EFIE) is usually formulated in spectral domain [17]. An alternative approach to the EFIE is the mixed potential integral equation introduced by Harrington [18] and later was used by different authors [19]. This technique uses Green's functions associated with the scalar and vector potentials which are expressed as Sommerfeld type integral [20].

In addition to the integral equation formulation for full-wave analysis of PC elements, finite-difference time-domain (FDTD) [21-24] and finite-element boundary-integral methods also have been used [25]. The FDTD method shows great promise in its flexibility in handling a variety of circuit configurations allowing an entire structure to be analyzed in one calculation. However, these "brute-force" methods require increased computer resources (e.g. memory, simulation times).

As mentioned before, we have developed two EM tools for the analysis of interconnects. The first is a 2D EM tool to analyze transmission line of uniform cross section. The second is a 3D tool to analyze isolated discontinuities (e.g. bends, tees, crosses, vias). For both of these tools we have developed very flexible meshing strategies. The user can configure the mesher to mesh elements to a given precision (e.g. 5 um) or to mesh certain "electrically large" object (e.g. ground planes) with mesh elements that exponentially grow in size away from the rest of the circuit (i.e. based on proximity to other objects). We plan to extend these mesh generator strategies to support new full-wave analysis approaches.

3.2.5 Analysis of Arrays

Application of microwave antennas in communications and radar always require highly directive antennas. Single microstrip elements have sizes around 0.5λ and are thus low-directivity radiators. For this reason they are grouped in arrays with the radiating fields of the elements adding in phase. The direction of the main beam is shifted by changing the phases of the signals fed to the radiating elements.

In the simplest approach, array performance is synthesized by summing radiating fields of each individual radiating element. The radiating field of each individual radiating element is simply computed from the current distribution, obtained in the absence of any other radiating elements.

More rigorously, the fields radiated by the array are obtained by adding the fields radiated by all the elements while taking into account the interaction among the elements [26]. The properties of a patch in the center of a very large array can be approximately determined by assuming that the array dimensions are infinite [27, 28, 30-32]. Floquet's theorem has been used to evaluate infinite periodic structure. Large phased arrays are commonly treated as infinite periodic arrays.

There are two approaches to finite arrays. First, small phased arrays are analyzed by techniques developed for the study of single elements, by considering the array as one multiply-connected antenna. Second, Ishimaru at al. [29] introduced a convolution technique to derive the characteristics of a finite array from those of an infinite one. This latter approach is not limited to small arrays, but requires a regular array *lattice*. Finally, the fast multipole method (FMM) [35] can accelerate the solution of the moment method by an order of magnitude and requires dramatically less storage for electrically large structures. It is an excellent candidate for the analysis of arrays.

3.3 EM Analysis Engines for Interconnect Analysis

At Tanner Research, two EM analysis products, L-Edit/2DEM and L-Edit/3DEM, have been under development. L-Edit/2DEM is being commercially offered. Development of L-Edit/3DEM is still underway but we anticipate that it will be completed will be completed by September 1996. Both products are tightly integrated with the L-Edit GUI.

3.3.1 L-Edit/2DEM:

L-Edit/2DEM is a two-dimensional quasi-static analyzer implemented by a boundary element method. The quasi-static approach allows fast simulation, while the boundary element discretization leads to accurate and general representations of the geometries. L-Edit/2DEM supports general transmission lines with arbitrary conductor cross-section geometries and arbitrary numbers of dielectric layers. An automatic mesh generator is embedded in L-Edit/EM. Simulation accuracy can easily be controlled by selecting the order of boundary elements and optional edge-enforced analysis. We plan to use L-Edit/2DEM as the EM engine in the Transmission Line Models approach to analysis of PC antennas. Moreover, L-Edit/2DEM can also be employed to analyze the transmission lines such as microstrip, stripline, coplanar waveguide, and coupled multilayered multiconductor transmission lines in the PC antenna circuits. The analysis results of transmission lines obtained using L-Edit/2DEM can also be used in the Multiple Network Approaches.

3.3.2 L-Edit/3DEM:

L-Edit/3DEM consists of a three-dimensional electrostatic analyzer for capacitance extraction and a three-dimensional magnetostatic analyzer for inductance extraction. L-Edit/3DEM computes self and mutual capacitances and frequency-dependent self and mutual inductances between conductors of complex shapes. A fast multipole algorithm is used in L-Edit/3DEM to accelerate the simulation. A set of automatic mesh generators is also embedded in L-Edit/3DEM. L-Edit/3DEM was designed to be used to analyze arbitrary vertical feed structures (and arrays of feed structures) in dense MCM designs, however, it will be equally applicable to any set of electrically small structures, especially vias and transmission line discontinuities in PC antenna circuits. The circuit models of vertical feed structures obtained using L-Edit/3DEM can be used in the multiport network approaches.

4 Array System Analysis and Synthesis

Antenna designs achieve a given set of performance specifications, and software tools are needed to examine the issues associated with meeting such specifications. We shall provide such a tool as part of our integrated design environment. This tool can be used to examine the realizability of a set of performance specifications, and to generate in turn realizable design specifications for fixed and adaptive antenna arrays.

Antenna arrays are used to realize aperture distributions with discrete radiating elements in order to obtain a desired radiation pattern. This tool shall also be used to determine the array element feed point amplitude and phase coefficients needed to realize such patterns.

4.1 System level trade-off analysis

At the system level, the most basic characteristics of an antenna can be examined. A link analysis, based on the Friis equations, can be used to examine frequency, size, link distance, and gain/power tradeoffs. A *link/loss-budget* can then be generated for determining where losses can be tolerated in the radiating system. Power dividing and phase shifting elements can have significant losses, and these losses need to be analyzed at the system level.

The link analysis is also used to determine the power requirements of the system, and to perform trade-off studies related to the exchange of antenna system gain vs. radiated power (or EIRP). Once an approximate value for gain is determined, the aperture size of the antenna system can be estimated. Although such calculations are approximate, they are more than adequate to identify the feasibility of a specific design.

4.2 Array Pattern Synthesis and Beam Forming

Part of the art of antenna design is to make the most effective use of the aperture (size) given. Using arrays, a specified aperture distribution can be constructed by driving the array elements at certain amplitude and phase levels, effectively sampling a continuous aperture distribution. The number of array elements, their spacing, and amplitude/phase coefficients are all variables in attempting to realize a given radiation pattern. In the case of an *adaptive* antenna, the number of elements and spacing must be selected carefully such that the desired radiation characteristics can be realized through certain amplitude/phase combinations. Care must also be taken to avoid designs that attempt to realize supergain: where dramatic variations in amplitude and phase will appear to give a desired response, but in reality system losses will cause the antenna to have a poor response.

The array analysis and synthesis tool shall provide several features associated with analyzing and synthesizing antennas based on their desired radiation characteristics. Once the aperture and configuration of the array have been determined, the user may specify a canonical pattern (e.g. Taylor or Dolph-Chebyshev). The tool will then compute the amplitude/phase coefficients required to obtain the desired radiation pattern.

The array analysis and synthesis tool shall also provide features for testing and determining the suitability of an antenna array for realizing user-specified (i.e. custom) radiation pattern. Such a feature is needed to determine if an antenna can be used effectively in an adaptive array algorithm or for digital beam-forming. The user will be able to specify custom radiation patterns that include sidelobe topography. Linear and area array pattern synthesis calculations for uniform arrays will be included in the tool. The tool shall be capable of generating or analyzing a set of array coefficients for the antenna.

In order to estimate the radiation patterns of manufacturable antenna arrays, it will be possible to select from a library of canonical radiating elements whose radiation patterns can be multiplied by the array factor resulting in a rapid, reasonably accurate calculation of the antenna array characteristics.

4.3 Sensitivity Analysis

Sensitivity analysis in the context of the array analysis tool is used to determine the impact of variations in the array coefficients on the radiation characteristics. It will be possible to specify tolerance values on a given array coefficient table that physically may be the result of feed structure losses, fabrication tolerances, and/or environmental factors. The sensitivity analysis will involve repeated calculation of the array's radiation characteristics with various coefficient table combinations being substituted based on the tolerance ranges. Superimposing these radiation pattern calculations will result in a *radiation pattern envelope* plot that graphically demonstrates the null-filling and main-beam instabilities caused by array coefficient variations.

A yield analysis of the radiation pattern envelope, due to amplitude and phase errors will be possible. For the case of digital phase shifts (for phased array and digital beam forming applications), we will support the specification of discrete phase values for the coefficients, providing a granularity analysis of the beam-steering capabilities will then be possible.

Sensitivity in the context of EM-level analysis is also important. At this level, yield and manufacturability are predicted and potential reasons for failure to meet specifications are identified. For example, the center frequencies of printed circuit antenna designs tend to be sensitive parameters, easily impacted by tolerances in material properties (e.g., dielectric constants), fabrication tolerances (metalization, etching), temperature, aging, and other environmental effects. As a result, shifts are possible in the resonant frequencies (center frequency, design frequency) of the patch antennas that can adversely effect:

- Radiated power (EIRP)
- Radiation pattern
- Sidelobe level
- Pointing angle

4.4 Partitioning of the array design for analysis

The final step in the antenna design process is to perform an accurate analysis of the entire array system in order to verify that the design specifications are indeed met.

Although in principle, the entire antenna sub-system can be analyzed using the EM simulation methods described earlier, this would not be the most efficient method. In many cases, portions of the antenna system—principally the feed and matching networks—are most appropriately analyzed using a frequency-domain circuit simulator. In many cases, well isolated transmission line environments (e.g. microstrip transmission lines) can be modeled quite accurately and quickly using this simulator.

Therefore we have proposed the following simulation approach. The Analysis Manager passes those sub-circuits, appropriate for EM simulation, to one of the EM engines. Those elements more efficiently analyzed using frequency domain circuit analysis methods are analyzed accordingly.

From the user's perspective, geometry capture of the array and its feed network is *automatic*, since the layout module also serves as an interface to the EM analysis engines. Internally, several steps are undertaken to setup either a high-frequency circuit analysis, or a full-wave EM analysis. The intricacies of the auto-routed feed network are extracted from layout and partitioned for circuit analysis. The radiating elements, and portions of the point feed for each, are partitioned for EM analysis.

4.5 High-frequency circuit analysis of the feed system

Although in principle the entire feed structure can be analyzed using the EM simulator engines described earlier, it would surely not be the most efficient method. The feed and matching networks are most appropriately analyzed using a frequency-domain circuit simulator. In many cases, well isolated transmission line environments (e.g. stripline) can be modeled quite accurately and quickly using this simulator.

Tanner Research has prototyped a linear, frequency-domain circuit simulator with antenna analysis capabilities. Using the circuit analysis program *Puff™* [36], originally developed at the California Institute of Technology, together with our EM simulation tools, we have been able to analyze both circuit problems (e.g. input impedance) and antenna problems (e.g. far field patterns).

A frequency domain circuit simulation (scattering parameter) analysis of the antenna feed system is used to identify the characteristics of the feed network. This analysis includes losses and dispersion of the feed element transmission lines, and an analysis of the discontinuities and lumped elements that make up the feed structures.

4.6 EM analysis of the antenna system

The multiple EM simulation engines discussed in Section 3.2 can be employed to perform the needed EM analysis for the antenna array verification. At the verification stage, accuracy takes priority over the simulation speed. Thus, high-order accuracy EM simulation engines such as the multiport network approach and the full-wave approach will be used for the verification tasks.

The full-wave analysis implemented by using the fast multipole method (FMM) can accelerate the solution of moment method by an order of magnitude and requires dramatically less storage for *electrically large* structures. Thus, FMM is an ideal candidate for an analysis and verification tool for printed antenna arrays.

4.7 Combined analysis of impedance and antenna array pattern

Once the circuit-level and EM-level analysis is performed, the results may be reassembled together with the passive element models, and a full-circuit, frequency domain simulation can be performed. This will result in the calculation of full-circuit level performance, including input impedance, radiation efficiency and antenna patterns—as a function of frequency

4.8 Failure Analysis

It is also important to be able to study the effects of failure of one or more radiating elements or the feed driving the element. We envision this as a post-design analysis step.

Adapting a phased array to this type of failure can be thought of in terms of performance optimization.

5 Prototype Design System Demonstration

On October 16, 1995 we presented a demonstration and viewgraph presentation at Ft. Monmouth outlining our Phase I accomplishments and highlights of our Phase II proposal. Included was a set of demos, showing antenna analysis, circuit analysis and a graphics display program enhanced for use with these other two tools. We demonstrated these tools running as applications under Windows 95. The combined viewgraph presentation and demonstration ran about three hours with questions.

In our presentation, we presented individual antenna array patterns analyzed using the transmission line method, and described how these results (and similar results derived using the cavity model) would be used to compute aggregate antenna array patterns. This computation involves convolving the individual element patterns with an appropriate array factor. Figure 5-1 depicts this approach, showing far-field patterns for both a uniformly distributed array and an array using a Taylor (uniform sidelobe level) distribution. Figure 5-1 was produced using Tanner's data visualization tool, W-Edit, running under Windows 95. W-Edit is a key component of the Comprehensive Array Design System, displaying radiation pattern and impedance data in a user-friendly graphical format. This contract provided direction and stimulated feature development for Version 2.0 of W-Edit due to be commercially released in April 1996.

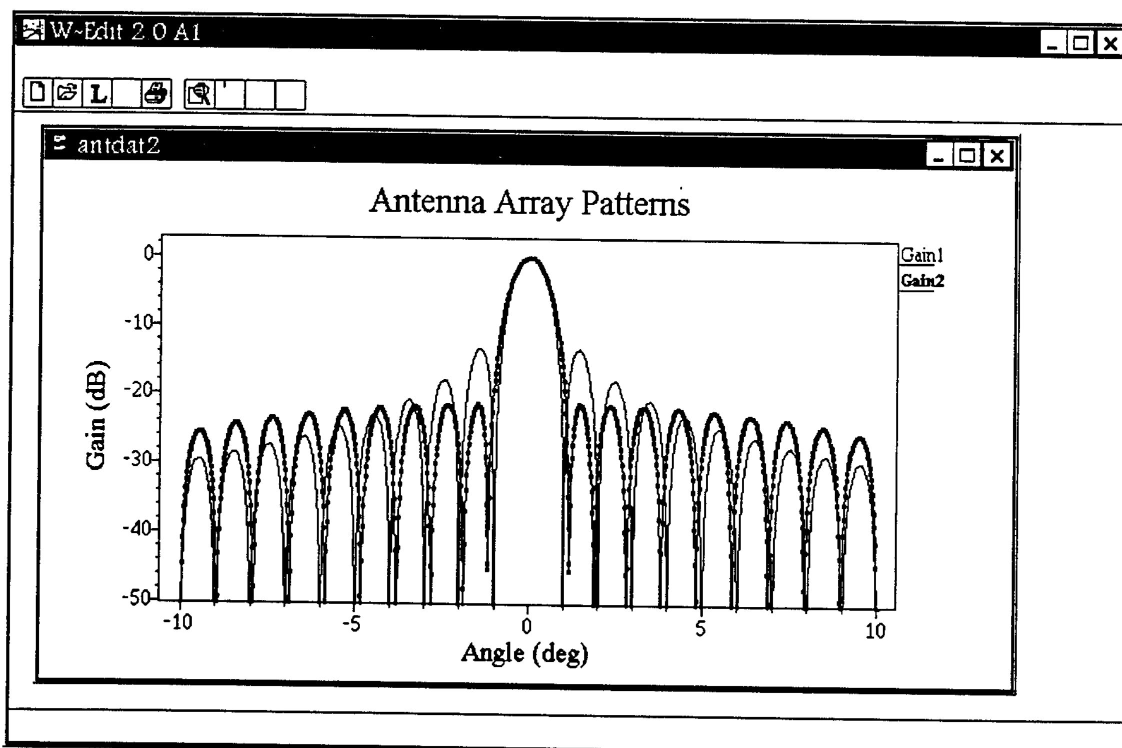

Figure 5-1: Far-field patterns for a uniformly distributed array and a Taylor array displayed using W-Edit.

6 References

[1] James, J.R., P.S. Hall, and C. Wood, *Microstrip Antenna Theory and Design*, London: Peter Peregrinus, 1981.

[2] Benalla, A. and K.C. Gupta. "Transmission Line Model for 2-port Rectangular Microstrip Patches with Ports at the Non-radiating Edges," *Electronics Letters*, Vol. 23, pp. 882-884, August 1987.

[3] Bahl, I.J., and P. Bhartia, *Microstrip Antennas*, Norwood, MA: Artech House, 1980.

[4] Lier, L. "Improved Formulas for Input Impedance of Coax-Fed Microstrip Patch Antennas," *Proc. IEE-H (MOA),* Vol. 129, pp. 161-164, 1982.

[5] Gupta, K.C. "Two-port Transmission Characteristics of Rectangular Microstrip Patch Radiators,"*1985 IEEE AP-S Int'l. Antennas Propagat. Symp. Dig.,* pp. 71-74.

[6] Chuang, S.L., L. Tsang, J.A. Kong, and W.C. Chew, "The Equivalence of the Electric and Magnetic Surface Current Approaches in Microstrip Antenna Studies," *IEEE Trans. Antennas Propagat.*, Vol. AP-28, pp. 569-571, 1980.

[7] Lo, Y.T., D. Solomon, and W.F. Richards,. "Theory and experiment on microstrip antennas," *IEEE Trans. Antenna Propagat.*, Vol. AP-27, pp. 137-145, March 1979. (B1)

[8] Carver, K.R., and J.W. Mink. "Microstrip Antenna Technology," *IEEE Trans. Antennas Propagat.,* Vol. AP-29, pp. 2-24, 1981.

[9] W. F. Richards, Y. T. Lo, and D. D. Harrison, "An Improved Theory for Microstrip Antennas and Applications," *IEEE Trans. Antenna Propagat.*, Vol. AP-29, pp. 38-46, 1981. (B2)

[10] Sorrentino, R. "Planar Circuits, Waveguide Models and Segmentation Method," *IEEE Trans. Microwave Theory Tech.,* Vol. 33, No 10, pp. 1057-1066, 1985.

[11] Gupta, K.C. "Planar Circuit Analysis," *in Numerical Techniques for Microwave and Millimeter-Wave Passive Structures,* T. Itoh, Ed., New York: Wiley, pp. 214-333.

[12] Gupta, K.C. "Multiport-Network Modeling Approach for Computer-Aided Design of Microstrip Patches and Arrays," *1987 IEEE AP-S Int'l. Symp. Antennas Propagat.,* Blacksburg, Virginia, 1987.

[13] Benalla, A. and K.C. Gupta, "Multiport-Network Model and Transmission Characteristics of Two-Port Rectangular Microstrip Antennas," *IEEE Trans. Antenna Propagat.*, Vol. AP-36, pp.1337-1342, 1988.

[14] Kuester, E.F. "Explicit Approximation for the Static Capacitance of a Microstrip Patch of Arbitrary Shape," *J. Electromagnetic Waves Appl.,* Vol.2 No. 1, pp.103-135, 1987.

[15] Pozar, D.M. "Input Impedance and Mutual Coupling of Rectangular Microstrip Antennas," *IEEE Trans. Antennas Propagat.,* Vol. AP-30, pp. 1191-1196, 1982.

[16] Benalla, A., K.C. Gupta, "Multiport Network Approach for Modeling the Mutual Coupling Effects in Microstrip Patch Antennas and Arrays," *IEEE Trans. Antennas Propagat.,* Vol. AP-37, pp.148-152, 1989.

[17] Lo, Y.T. at al., "Microstrip antenna," In K. Chang, ed., *Handbook of Microwave and Optical Components,* Vol. 1, Chapter 13. New York: John Wiley & Sons, 1989.

[18] Harrington, R.F. "Field Computation by Moment Methods," New York: Macmillan, 1968.

[19] Mosig, J.R. "Arbitrary Shaped Microstrip Structures and Their Analysis with a Mixed Potential Integral Equation," *IEEE Trans. Microwave Theory Tech.,* Vol. 36, No 2, pp. 314-323, 1988.

[20] Mosig, J.R., F.E. Gardiol, "Analytical and numerical techniques in the Green's function treatment of microstrip antennas and scatterers," *Proc. Inst. Elec. Eng.,* Pt. H, Vol. 130, pp.175-182, 1983.

[21] Reineix R., B. Jecko. "Analysis of Microstrip Patch Antennas Using Finite Difference Time-Domain Method," *IEEE Trans. Antennas Propagat.,* Vol. AP-37, No. 11, pp.1361-1368, 1989.

[22] Sheen, D.M., M.D. Abouzahra, J.A. Kong, "Application of the Three-Dimensional Finite Difference Time-Domain Method to the Analysis of Planar Microstrip Circuits," *IEEE Trans. Microwave Theory Tech.,* Vol. 38, No. 7, pp. 849-857, 1990.

[23] Wu, C. et al. "Modeling of Coaxial-Fed Microstrip Patch Antennas Using Finite Difference Time-Domain Method," *Electronics Letters,* Vol. 27, No 19, pp.1691-1692, 1991.

[24] Wu, C. et al. "Accurate Characterization of Planar Printed Antennas Using Finite Difference Time-Domain Method," *IEEE Trans. Antennas Propagat.,* Vol. AP-40, No. 5, pp. 526-534, 1992.

[25] Jin, J.-M., Volakis, J.L., "A Hybrid Finite Element Method for Scattering and Radiation by Microstrip Patch Antennas and Arrays Residing in a Cavity," *IEEE Trans. Antennas Propagat.,* Vol. AP-39, No. 11, pp. 1598-1604, 1991.

[26] Bhattacharyya, A.K., L. Shafai, "Surface Wave Coupling between Circular Patch Antennas," *Electron. Letters,* Vol. 22, No. 22, pp. 1198-1200, 1986.

[27] Pozar D.M. "General Relations for a Phased Array of Printed Antennas Derived from Infinite Current Sheets," *IEEE Trans. Antennas Propagat.,* Vol. AP-33, pp. 498-504, 1985.

[28] Pozar D.M. "Analysis and Design Considerations for Printed Phased-Array Antennas," in *Handbook of Microstrip Antennas,* J.R. James and P.S. Hall, Eds., Vol. 1, Chap. 12, London: Peter Peregrinus.

[29] Ishimaru, A., R.G. Coe, G.E. Miller, W.P. Geren. "Finite Periodic Structure Approach to Large Scanning Array Problems," *IEEE Trans. Antennas Propagat.,* Vol. AP-33, pp. 1213-1220, 1985.

[30] Pozar, D.M. "Scanning Characteristics of Infinite Arrays of Printed Antenna Subarrays," *IEEE Trans. Antenna Propagat.*, Vol. 40, No. 6, pp. 666-674, 1992

[31] Aberle J.T., D.M. Pozar, J. Manges, "Phased Arrays of Probe-Fed Stacked Microstrip Patches," *IEEE Trans. Antenna Propagat.*, Vol. 42, No. 7, pp. 920-927, 1994.

[32] Aberle J.T., D.M. Pozar, "Accurate and Versatile Solutions for Probe-fed Microstrip Patch Antennas and Arrays," *Electromagnetics,* Vol. 11, pp. 1-19, 1991.

[33] P. Hammer, D. Van Bouchaute, D. Verschraeven, and A. Van de Capelle, "A model for calculating the radiation field of microstrip antennas," *IEEE Trans. Antennas and Propagat.*, Vol. AP-27, pp. 267-270, February 1979.

[34] H. Pues and A. Van de Capelle, "Accurate transmission-line model for the rectangular microstrip antenna," *IEE Proc. H.*, Vol. 131(6), pp. 334-340, 1984.

[35] L. R. Hamilton, et al, "Fast Multipole Methods for Scattering Computation," Final Report on Contract No. F49620-91-C-004 Air Force Office of Scientific Research, 110 Duncan Ave., Suite B115, Bolling Air Force Base, DC, 20332-0001.

[36] Rutledge, D.B., R.C. Compton, S.W. Wedge, "Puff; Computer-Aided Design for Microwave Integrated Circuits.", Calif. Institute of Technology, Pasadena, CA, 1991.

7 Appendix A: Specification of the Transmission Line Model and the Cavity Model

This appendix contains the specification of the algorithms on which the Transmission Line Model and the Cavity model codes which were developed on Phase I. The results of analyzing concrete, practical examples are contained in Sections 3.2.1 and 3.2.2.

A1: Transmission Line Model Specification

In this model, a rectangular patch is viewed as a resonant section of a microstrip transmission line. This method offers a very fast simulation for rectangular patch antennas.

Figure A1 shows a rectangular microstrip antenna of patch width W and length L, where L is the resonant dimension of the fundamental radiating mode. The field underneath the patch is assumed to be constant along the width W for the fundamental radiating mode. In this configuration, the feed structure can be either an end feed through a coplanar microstrip line or a coaxial feed.

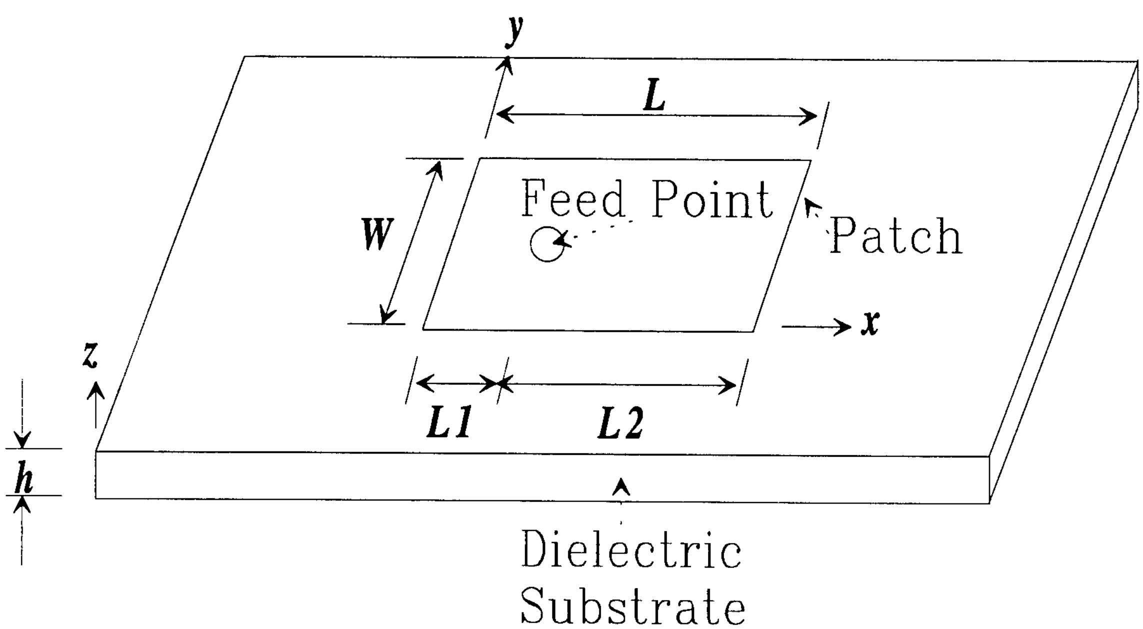

Figure A1: Geometry of a rectangular patch antenna

The radiating mechanism is investigated by using the equivalence principle. The radiating element consists of four radiating slots. These so-called equivalent slots are two main slots with a uniform distribution and two side slots with a sinusoidal distribution. The main slots locate at the ends of the patch, while the two side slots locate at the side edges of the patch. Using the aperture model, the radiation field of the microstrip antenna can be simply calculated. A detailed derivation and a complete set of formulations can be found in [A1]. Figure A2 shows the equivalent slots of the microstrip antenna. In Figure A2, Δl is the open-end extension of the patch considered as a (semi-infinite) microstrip line of width *W*. The expression given in [A2] has been employed to compute Δl.

To compute the input impedance of the rectangular patch antenna, a circuit representation needs to be established. The circuit representation of the transmission line model is shown in Figure A3. In this network, *Ys* is the self admittance of the main radiating slots, *Ym* is their mutual (radiative) admittance, *Yc* is the characteristic admittance of the microstrip line formed by the patch, and $\gamma = \alpha + j\beta$ is the complex propagation constant.

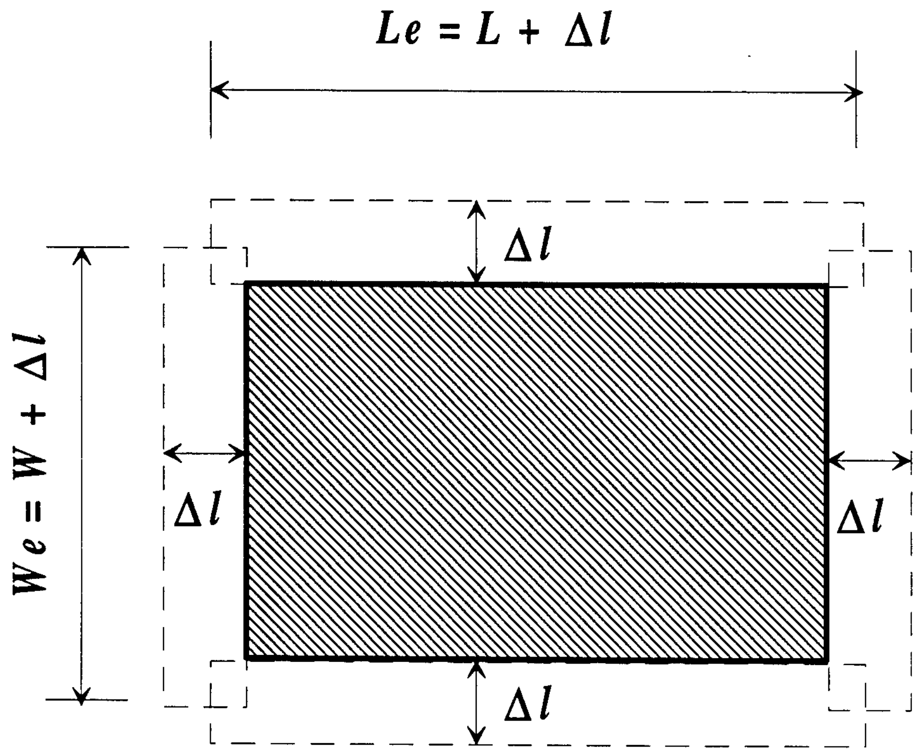

Figure A2: Four-slot aperture radiation model

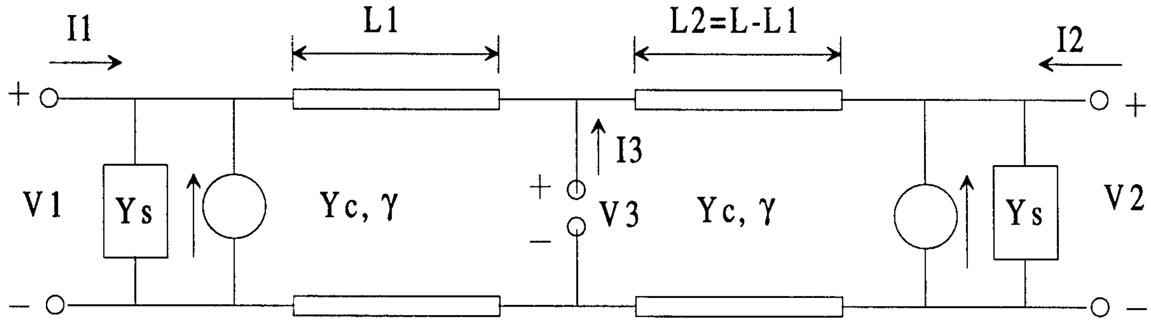

Figure A3: Circuit representation of the transmission line model

The admittance matrix of this three-port model is given by

$$[Y]=\begin{bmatrix} Y_s+Y_c\,coth(\gamma L_1) & -Y_m & -Y_c\,csc\,h(\gamma L_1) \\ -Y_m & Y_s+Y_c\,coth(\gamma L_2) & -Y_c\,csc\,h(\gamma L_2) \\ -Y_c\,csc\,h(\gamma L_1) & -Y_c\,csc\,h(\gamma L_2) & Y_c\,coth(\gamma L_1)+Y_c\,coth(\gamma L_2) \end{bmatrix}, \qquad \text{(A1)}$$

where *coth(z)* and *csch(z)* are the complex hyperbolic cotangent and cosecant functions of argument z.

If there is only one feed point on one of the ports, an input admittance can be defined by assuming that two other ports are open-circuit. For instance, for a microstrip antenna fed by a coplanar microstrip line at $x = 0$, the input admittance can be obtained from equation (10) as

$$Y_{in}=\left.\frac{I_1}{V_1}\right|_{I_2=I_3=0}=\frac{Y_c^2+Y_s^2-Y_m^2+2Y_sY_c\,coth(\gamma L)-2Y_mY_c\,csc\,h(\gamma L)}{Y_s+Y_c\,coth(\gamma L)}. \qquad \text{(A2)}$$

Similarly, the input admittance for a coaxial feed can be obtained from equation (A1) by assuming $I_1 = I_2 = 0$.

A2: Cavity Model Specification

The cavity model approach can be employed to analyze various patches of regular shapes. The cavity model is a two-dimensional model, which offers considerable improvement over the one-dimensional transmission line model. Moreover, the cavity model can be expended into multiport network model, which is able to handle a more general shapes through the segmentation and de-segmentation techniques. Here, a prototypical cavity model has been implemented and a set of C programs has been developed to analyze the rectangular and circular patch antennas. Figure A3 shows geometry of a circular microstrip antenna with radius a.

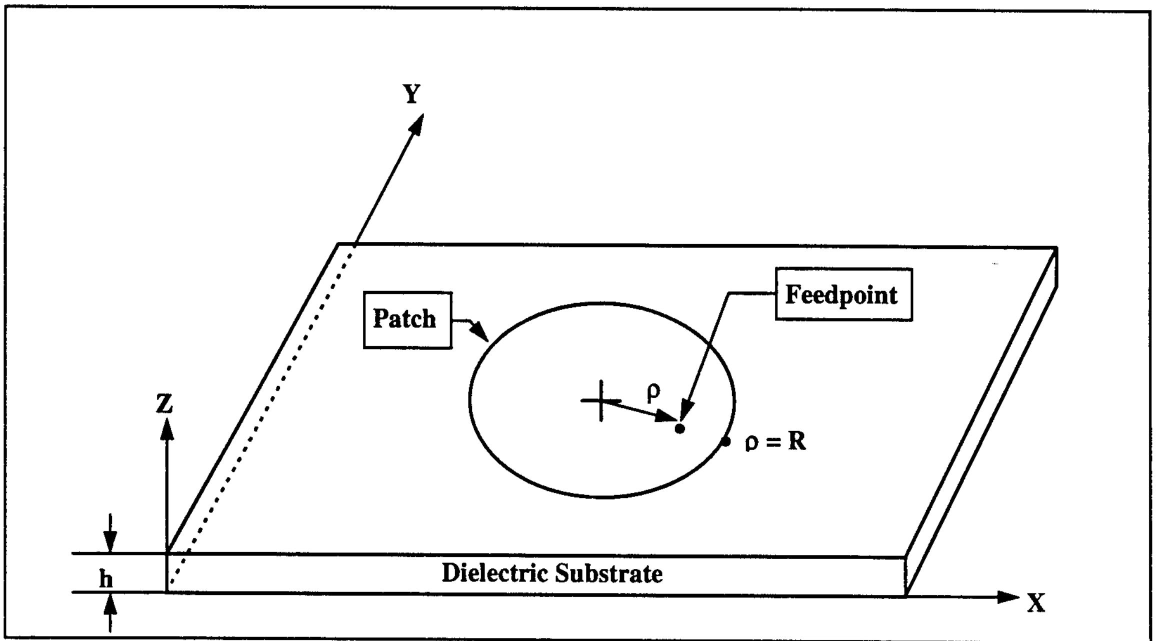

Figure A3: Geometry of a circular microstrip antenna

A cavity model for the microstrip antennas is based on the following observations: (a) The close proximity between the microstrip antenna and the ground plane suggests that the electric field $\boldsymbol{E}$ has only the z-component and $\boldsymbol{H}$ has only the xy-components in the region bound by the microstrip and the ground plane. (b) The fields underneath the patch is independent of the z-coordinate. (c) The electric current in the microstrip must have no component normal to the edge at any point on the edge, implying a negligible tangential component of $\boldsymbol{H}$ along the edge. Therefore, the region between the microstrip and the ground plane can be treated as a cavity bounded by a magnetic wall along the edge and by electric walls from above and the below.

The electric field E_z is given in terms of the resonant modes ψ_m of the cavity by

$$E_z = j\omega\mu \sum_m \frac{1}{k^2 - k_m^2} \frac{\langle J, \psi_m \rangle}{\langle \psi_m, \psi_m \rangle} \psi_m, \tag{A3a}$$

where J denotes the feed current, $\langle J, \psi_m \rangle = \int J\psi_m^* ds$ and $\langle \psi_m, \psi_m \rangle = \int \psi_m \psi_m^* dv$. Thus, the magnetic field can be obtained as

$$\boldsymbol{H} = -\frac{j}{\omega\mu} \hat{z} \times \nabla E_z. \tag{A3b}$$

The resonant modes of various regular patches have been listed in [4]. In particular, for a rectangular patch, one has $\psi_{mn} = cos\left(\frac{m\pi}{L}x\right)cos\left(\frac{n\pi}{W}y\right)$ and $k_{mn} = \sqrt{\left(\frac{m\pi}{L}\right)^2 + \left(\frac{n\pi}{W}\right)^2}$. For a circular patch, one can obtain $\psi_{mn} = J_n(k_{mn}\rho)e^{jn\phi}$ and $J_n'(k_{mn}a) = 0$, where ρ and ϕ are the polar coordinates on the xy-plane, and $J_n(\cdot)$ is the first kind, n-th order Bessel function.

The equivalent magnetic current source on the magnetic wall along the edge can be obtained as

$$K = 2\hat{n} \times \hat{z}E_z, \tag{A4}$$

where $\hat{n}$ is the outward normal to the magnetic wall, and the factor of 2 accounts for the presence of the ground plane. The electric vector potential is given by

$$F(r) = \varepsilon_0 \int_{magnetic\,wall} \frac{K(r')}{4\pi|r - r'|} e^{-jk_0|r-r'|} ds', \tag{A5}$$

and the far field can be obtained as

$$E_\theta = j\omega\eta F_\phi = j\omega\eta\left(-F_x \sin\phi + F_y \cos\phi\right), \tag{A6a}$$

$$E_\phi = -j\omega\eta F_\theta = -j\omega\eta\left(-F_x \cos\theta \cos\phi + F_y \cos\theta \sin\phi\right). \tag{6b}$$

The input admittance Y can be computed as follows [5]:

$$Y = \left[P + j2\omega\left(W_E - W_M\right)\right]/|V|^2, \tag{A7}$$

where W_E is the time-averaged electric stored energy, W_M is the time-averaged magnetic stored energy, V equals the driving point voltage which equals hE averaged over the feed strip or coaxial line, and P is the total power that is sum of the radiated power P_r, the conducting loss P_c, the dielectric loss P_d and the surface wave power P_{sw}. In general, the surface wave power is only on the order of a few percent of the total power and thus may be neglected. The detailed formula for computing the radiated power, the conducting loss and dielectric loss can be found in [A4].

A3: References:

[A1] P. Hammer, D. Van Bouchaute, D. Verschraeven, and A. Van de Capelle, "A model for calculating the radiation field of microstrip antennas," *IEEE Trans. Antennas and Propagat.*, Vol. AP-27, pp. 267-270, February 1979.

[A2] M. Kirschning, R. H. Jansen, and N. H. L. Koster, "Accurate model for open end effect of microstrip lines," *Electronics Lett.*, **17**(3), pp. 123-125, 1981.

[A3] H. Pues and A. Van de Capelle, "Accurate transmission-line model for the rectangular microstrip antenna," *IEE Proc. H.*, **131**(6), pp. 334-340, 1984.

[A4] Y. T. Lo, D. Solomon & W. F. Richards, "Theory and experiment on microstrip antennas," *IEEE Trans. Antenna Propagat.*, Vol. AP-27, pp. 137-145, March 1979.

[A5] W. F. Richards, Y. T. Lo, and D. D. Harrison, "An Improved Theory for Microstrip Antennas and Applications," *IEEE Trans. Antenna Propagat.*, Vol. AP-29, pp. 38-46, 1981.